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A Review of Air to Air Heat Exchangers (ATAHE's) for Well Sealed Homes

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Historically, air-to-air heat exchangers (ATAHE's) have been used in office, commercial and industrial buildings. More recently, however, there has been a new demand for ATAHE's with smaller capacities, on the order of 150 L/s or less, for application in residential buildings. In this context, this study focuses on ATAHE's designed for application in super energy efficient (SEE) or other well sealed homes.

In leaky homes ventilation air comes through the cracks and openings in the shell. Since there is no control of air lost through the leaks it is impractical to recover heat from this air. In a super energy efficient (SEE) or other well sealed home, mechanical ventilation is needed. An ATAHE can be included in the ventilation system to preheat incoming fresh air with energy recovered from air exhausted from the home.

At present, the market for residential ATAHE's is small. The use of residential ATAHE's, however, is expected to grow with the popularity of the market for well sealed homes, encouraged by government incentive and consumer demand.

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2.1 What is an ATAHE?

An air-to-air heat exchanger is a device which transfers energy from a warm air stream to a cooler air stream. Most super energy efficient or other well sealed homes have mechanical ventilation systems with a separate fresh air intake and exhaust air outlet which are easily adaptable to heat recovery with ATAHE's.

The effectiveness of an ATAHE is defined as the ratio of the heat which is actually transferred to the maximum theoretical heat transfer. Physical limitations prevent 100% effectiveness; residential ATAHE's generally have an effectiveness between 40% and 80%.

Heat recovery in ATAHE's may involve transfer of sensible and latent heat. Sensible heat transfer is associated with the temperature drop or gain of the air passing through the heat exchanger. Latent heat transfer is associated with the transfer of water vapour from one air stream to the other.

In residential ATAHE's the primary mode of heat transfer is sensible heat transfer. A sizable amount of latent heat transfer can take place as well.

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Certain types of ATAHE's such as capillary blowers, rotary type and those with permeable paper cores transfer some moisture. Since one of the primary functions of the ventilation system is to control humidity levels, larger air flow rates may be needed for humidity control in the home if this type of ATAHE is installed.

In cold weather condensation may occur in the heat exchanger in the exhaust air stream. The amount of water vapour that can be held in air decreases with temperature. Therefore, once the water vapour begins to condense, any further decrease in the temperature of the exhaust air stream will result in increased condensation. For this reason, most residential ATAHE's have a condensate drain, and provision for a defrost cycle should further cooling cause frost build-up.

There currently is no accepted standard for measurement of the effectiveness of residential ATAHE's. The values published by manufacturers have been obtained using various methods, and cannot be directly compared. The actual overall effectiveness will vary with air flow rates, defrost cycles, etc. The Canadian Standards Association is currently preparing a performance standard for residential ATAHE's. This standard will establish the criteria for rating ATAHE's and allow for an acceptable method of comparing the various manufacturers' ATAHE's.

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2.2 Types of ATAHE's

Plate type exchangers are most commonly used for residential applications. Residential size heat pipe heat exchangers and capillary blowers are also available, and one distributor will soon be marketting a rotary type. There are a number of other types of exchangers (i.e. regenerative, thermosyphon, coil and heat pump), but they are not readily available for residential applications in Canada. Descriptions of the plate-type, heat pipe, rotary and capillary blower heat exchangers follow.

Plate Type Heat Exchangers

This is the type of heat exchanger most commonly available for use in residential applications. Basically, a 'sandwich' of thin plates is used to separate the air streams, with exhaust and fresh air passing through alternate separations (that is, fresh air flows through every second space, and exhaust air flows through the spaces between).

The plates are arranged to maximize the surface area over which the air streams pass. Heat flows from one air stream to the other through the thin plates due to a temperature difference between the two air streams.

The plates are constructed of various materials, including aluminum, glass, polypropylene, polyethylene, treated paper, ABS, styrene, etc.

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A schematic of a plate-type heat exchanger is shown in Figure 2.1. These heat exchangers are simple in construction, with no moving parts except fans, and are generally reliable. Cross leakage (mixing of the exhaust air stream with the fresh air stream) is low if the seals at the edges of the plates are properly designed and installed. The thermal effectiveness for plate-type exchangers is in the range of 40% to 80% for most design flow rates.

Provision for automatic defrost is normally required.

Heat Pipe Heat Exchangers

A heat pipe is a device, in appearance a plain straight pipe sealed at both ends, which can conduct heat extremely effectively. It is charged with a working fluid (such as a refrigerant) which acts as a heat transfer medium. Heat is transferred into one end of the tube and absorbed by the liquid working fluid (refer to Figure 2.2a). The fluid vaporizes and is propelled by locally increased vapour pressure toward the colder end of the heat pipe. Here the vapour condenses, releasing its latent heat through the heat pipe wall.

A wick structure is used to return the working fluid to the evaporation section while ensuring an even distribution of working fluid on the inner wall of the heat pipe.

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A schematic of a heat pipe heat exchanger is shown in Figure 2.2b. The exhaust air stream passes the condensor side of the heat pipes while the incoming fresh air stream passes the evaporator side. The air streams are separated by a plate through which the heat pipes pass.

Heat pipes for residential applications are normally made of aluminum or copper and contain a non-toxic working fluid such as a Freon. Heat transfer may be enhanced by the addition of metal fins.

These heat exchangers have no moving parts except fans. Cross leakage is usually very low. Thermal effectiveness for heat pipe heat exchangers is in the range of 60% to 80% for most design flow rates.

Defrost is normally required.

Rotary Heat Exchangers

A basic component of a rotary heat exchanger is the heat transfer core, often referred to as a 'heat wheel'. As this core rotates in the heat exchanger casing, any given point on the core passes alternately through the supply and exhaust air streams. Energy is transferred from the warm air stream to the heat transfer medium (the core) which then transfers the energy to the cooler air stream. A schematic of a rotary heat exchanger is shown in Figure 2.3.

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Heat transfer media can be made of metallic and non-metallic materials. Examples are woven aluminum, corrugated aluminum foil and permeable synthetic foam.

Rotary heat exchangers require two fans, one for each air stream, normally built into the unit. In addition, there is a power requirement for the rotating core. There is some cross leakage and moisture transfer with these heat exchangers. Defrost is not normally required. Thermal effectiveness can range from 60% to 80%.

Capillary Blowers

Capillary blowers eliminate the need for a separate fan by combining the heat exchanger core and the means of moving the air into one element. This type of unit is very simple in design and is compact.

The blower is comprised of a permeable material which, when rotated, generates an air flow by centrifugal action. Supply and exhaust streams are separated by a baffle on the inside of the permeable ring and by ducts on the outside. Like with the heat wheel, heat exchange takes place as elements of the permeable ring pass alternately between the cold and warm air streams. A schematic of a capilliary blower is shown in Figure 2.4.

Cross leakage and moisture transfer occur with this type of heat exchanger. Defrost is not normally required. Thermal effectiveness generally ranges from 40% to 50%.

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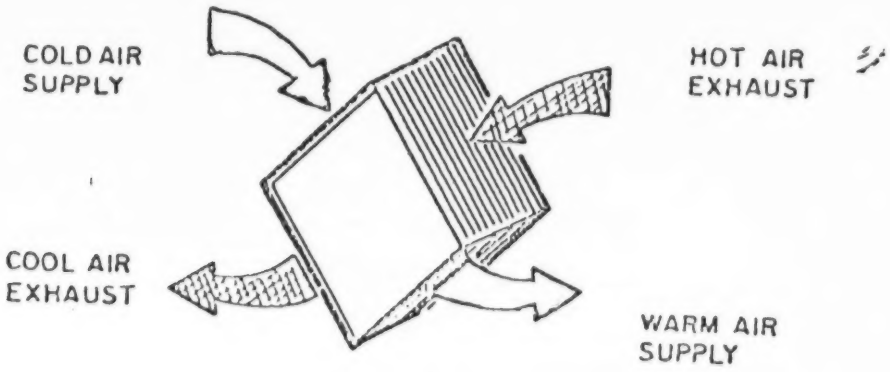
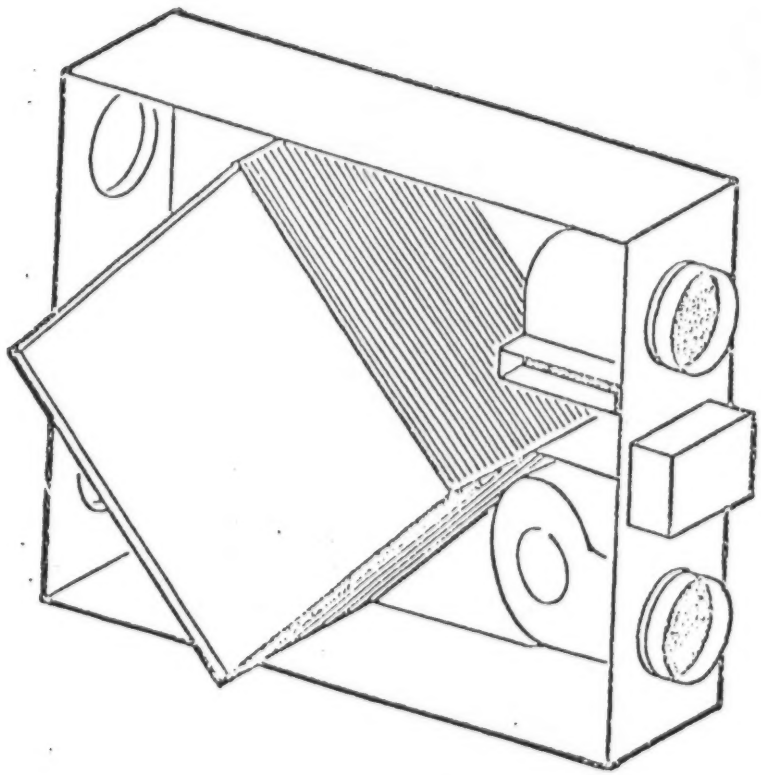


A)



B)

FIGURE 2.1 - a) Schematic of a Plate-Type Heat Exchanger Core
b) Cut-Away View of a Plate-Type Heat Exchanger

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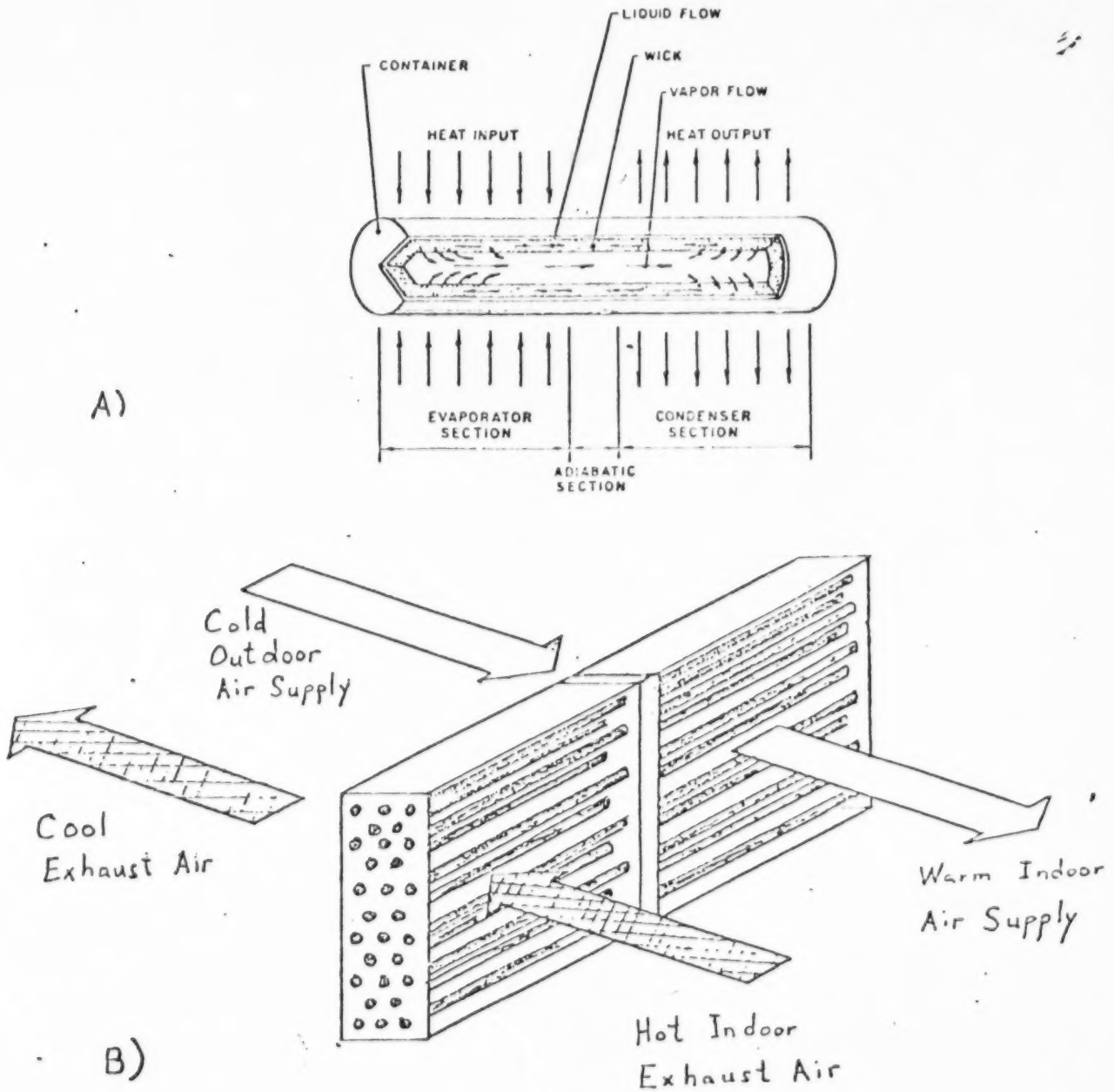

FIGURE 2.2 - a) Schematic of a Heat Pipe
b) Schematic of a Heat Pipe Heat Exchanger

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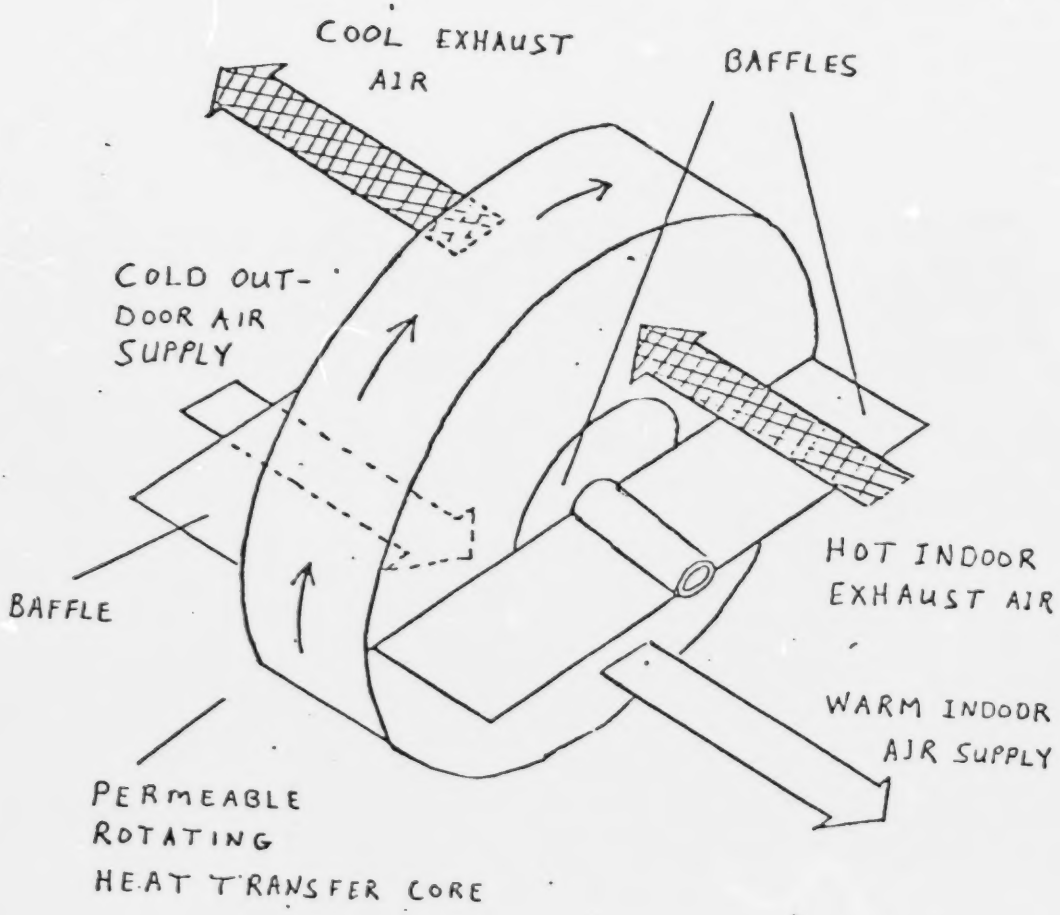

FIGURE 2.3 Schematic of a Rotary Heat Exchanger

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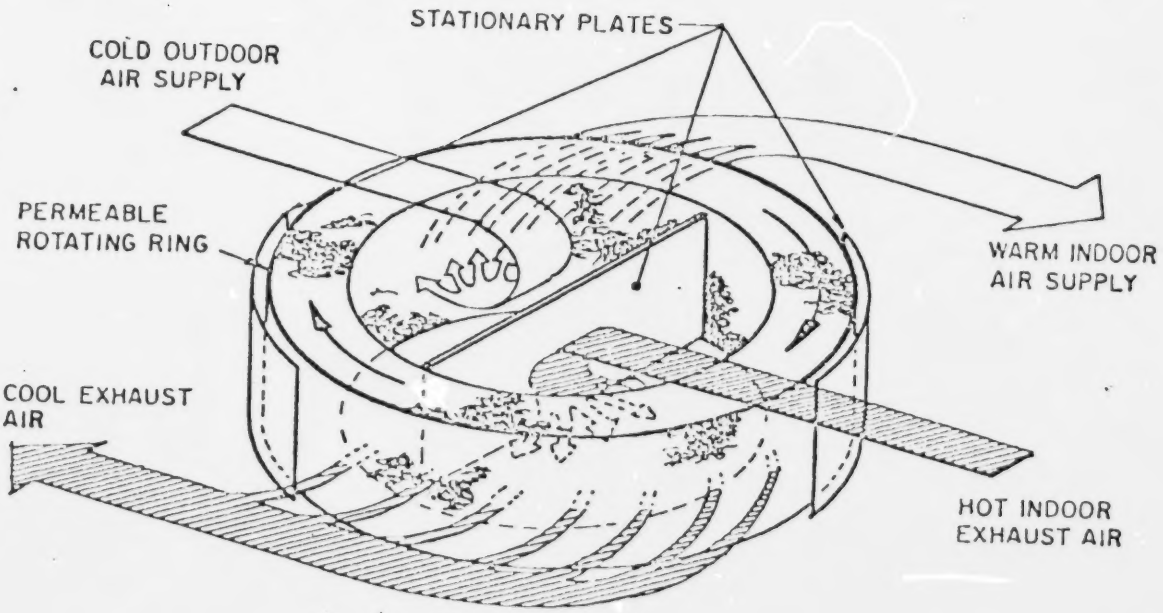

FIGURE 2.4 - Schematic of a Capillary Blower Heat Exchanger

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2.3 Sizing the ATAHE

ATAHE's are designed to operate for a certain range of air flows. Selection of a heat exchanger will depend on the required ventilation rate for the house, and the pressure drop through the air distribution network of the ventilation system. The longer and more complex the ductwork, the higher is the pressure drop and the corresponding required fan capacity.

Recent studies indicate a ventilation rate of 0.5 air changes per hour may be the maximum required to reduce contaminants and moisture to acceptable concentrations. An exception is for ATAHE's designed for humidity transfer, where higher flow rates than those corresponding to 0.5 air changes per hour may be needed to maintain acceptable humidity levels in the home.

An example of how to calculate the required capacity of the ATAHE follows. A typical house with a floor area (including basement) of 200 square metres, and a ceiling height of 2.5 metres, has a volume of 500 cubic metres. Based on 0.5 air changer per hour, the maximum required flow rate would be 250 cubic metres per hour, or 70 litres per second. (To convert cubic metres per hour to litres per second, divide by 3.6.)

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2.4 Cost

There are about a dozen manufacturers currently serving the Canadian market with residential ATAHE's. A December 1982 survey shows the suggested retail price of these units varies from $500 to $1,100, with an average price of about $800. Installation costs are not included in these prices.

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All commonly available residential heat exchangers require that both fresh air and exhaust air be brought close together at one point. For ducted heat exchangers, this means that supply and exhaust duct systems are necessary. Figure 3.1 shows a typical installation.

3.1 Fresh Air Intake

A fresh air duct is required to bring in air from outside, to the heat exchanger. Since this air will be at outside temperatures, this duct should be insulated and covered with a vapour barrier to prevent condensation. The fresh air intake should be located where it will not be blocked by grass cuttings, leaves or snow, away from driveways where automobile exhaust fumes are generated, and should be equipped with a coarse screen, or 'bird screen'. The bird screen should be of coarse mesh, as fine mesh (such as for window screening) will tend to quickly block with insects - cutting off fresh air supply to the home. Insects and other small particles will be trapped in the air filter located in the fresh air duct leading into the ATAHE. This filter should be readily accessible for cleaning or replacement.

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3.2 Fresh Air Distribution

The fresh air leaving the heat exchanger should be ducted to some point where it can be distributed throughout the house. If the home is equipped with a forced air heating system, the fresh air can be discharged near a return grill of the heating system, as shown in Figure 3.1. For a furnace with intermittent fan operation, the fresh air duct should not be connected directly to the furnace return air system. Intermittent operation of the furnace fan may cause unbalanced flow in the ATAHE.

An alternate method for fresh air distribution is shown in Figure 3.2. The fresh air duct from the ATAHE is connected directly to the furnace return air system with the stipulation that the furnace fan is always operating (if the fan is not always operating, unbalanced flows may occur). Thus fresh air is continuously distributed throughout the house, and is intermittently heated by the furnace on a demand basis. This method should only be used where it is not prohibited by local codes and for heat exchangers which do not defrost by shutting down the fresh air supply fan. Since a furnace fan normally operates with a much greater air flow rate than an ATAHE, there will be improved air circulation in the house. There are increased costs for operating this fan continuously, however.

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For houses without a forced air heating system (such as those with hot water or electric baseboard heating), the fresh air should be ducted to individual rooms, as shown in Figure 3.3. A more powerful intake fan may be required because of the more complex distribution system.

Some ATAHE manufacturers recommend that the fresh air be discharged near ceiling level, so that it mixes with the warm air at the top of the room. This is done to help avoid cold drafts, and to make use of potentially available passive solar heat. It can also help destratify air (i.e. much warmer air near the ceiling than the floor) which is particularly likely where there are cathedral ceilings.

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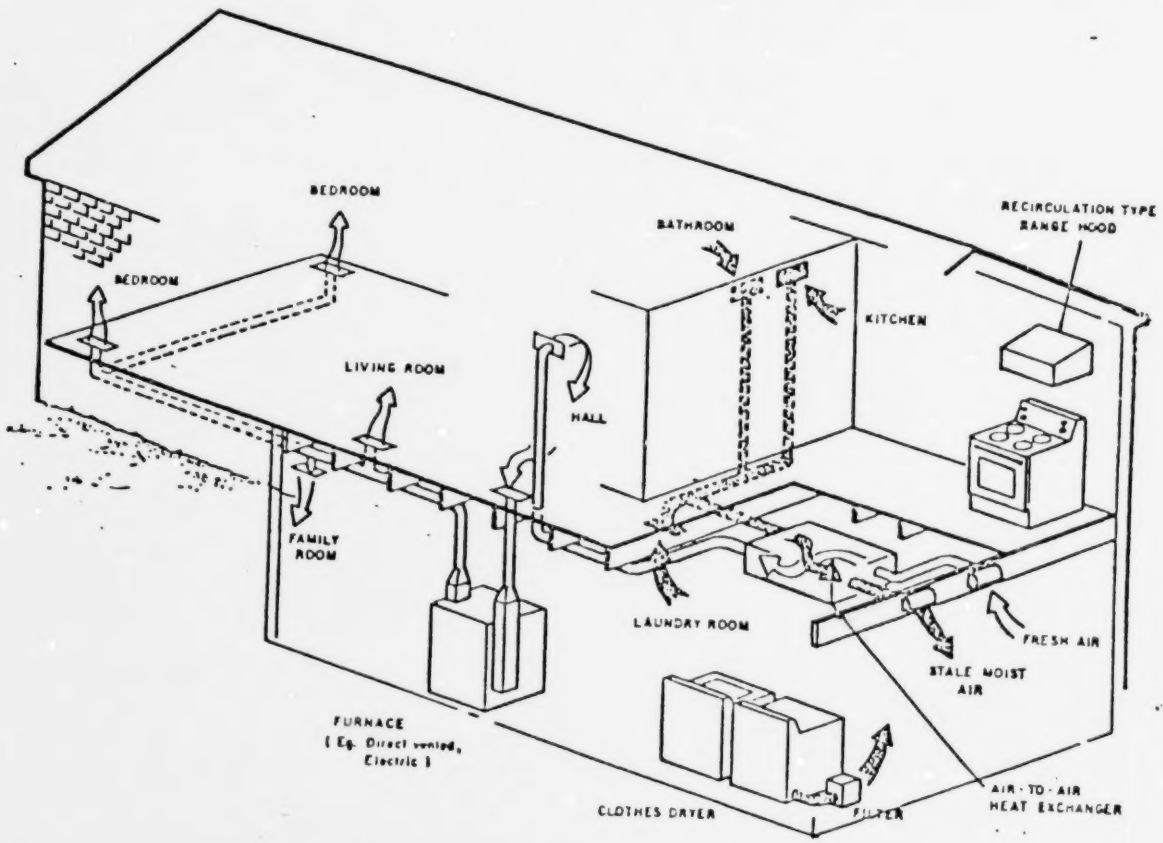

Advantages - Simple ductwork configuration for ATAHE

Disadvantages - When furnace is not operating, air distribution in the home relies on natural convection.

Caution - Do not connect fresh air supply to the return air plenum because intermittant furnace fan operation will likely cause unbalanced flows in the ATAHE.

FIGURE 3.1 - ATAHE Installation with Forced Air Heating System and Intermittent Furnace Fan Operation. The fresh air from the ATAHE is not connected directly to the return air plenum.

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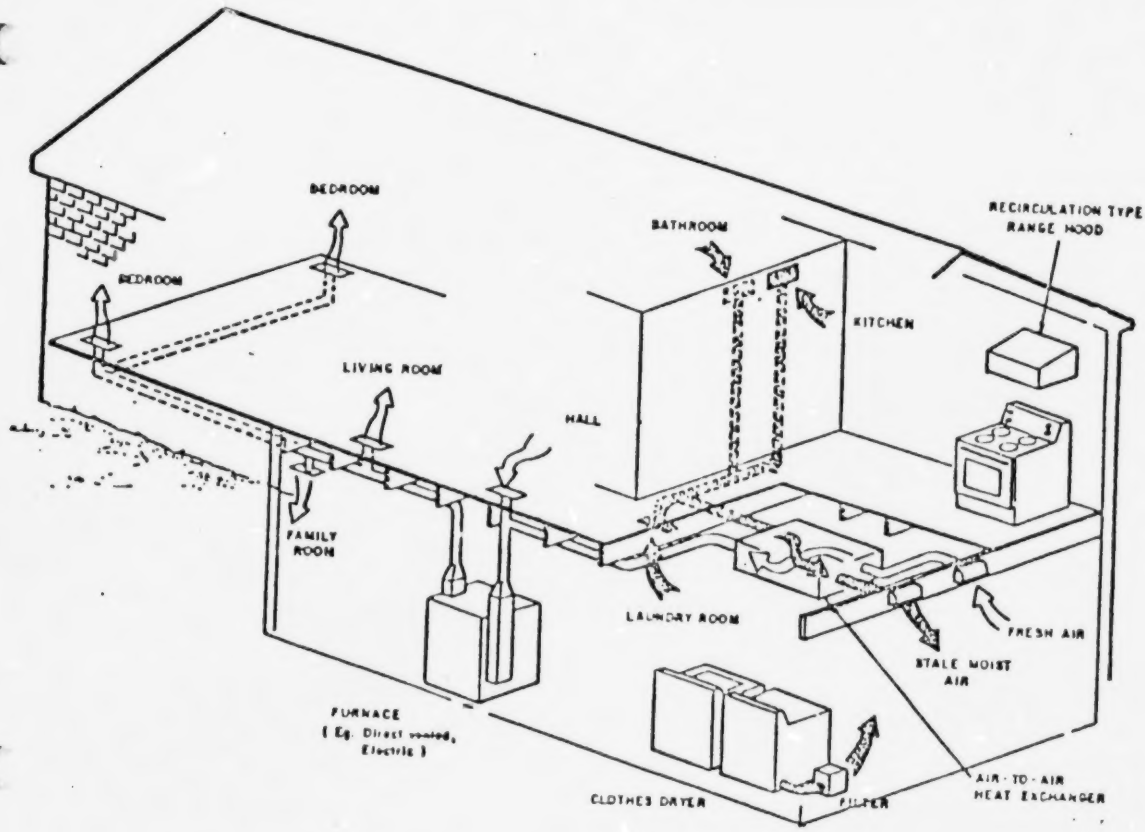

Advantages - Provides good circulation of air throughout the home.

Disadvantages - Higher operating cost as two fans (at the ATAHE and at the furnace) are required to operate continuously to distribute supply air.

Caution - Furnace fan must operate continuously. Special care must be taken by installer so that the system is properly balanced. Do not use for heat exchangers which defrost by shutdown of fresh air fan.

FIGURE 3.2 - ATAHE Installation with Forced Air Heat System and Continual Furnace Fan Operation. The fresh air from the ATAHE is connected to the return air duct work of the furnace. The ATAHE is not the sole source for return air.

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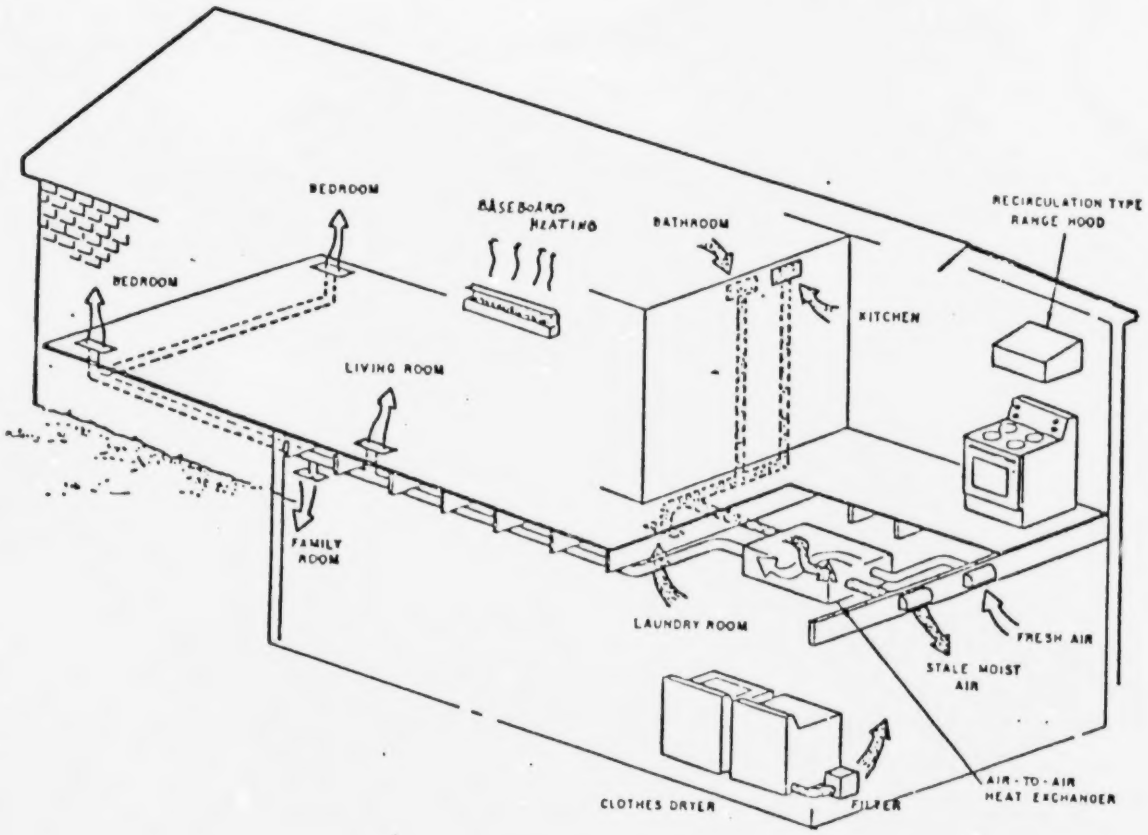

Advantages - There is continuous forced air circulation.

Disadvantages - Potential for cold draughts.

Caution - A more powerful supply air fan may be needed than is provided with a packaged ATAHE.

FIGURE 3.3 - ATAHE Installation with Baseboard Heating

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3.3 Exhaust Air Collection

The exhaust air should be taken from areas where contaminants and moisture are normally in greatest quantities, (i.e. the bathroom, kitchen and laundry room). (See Figures 3.1, 3.2 and 3.3.)

Rangehood vents should not be connected directly to the exhaust system, since the grease contained in this type of exhaust can build up on the heat exchanger surfaces and tend to plug it. Kitchen range hoods should be of the recirculation type with grease traps and charcoal filters for odour removal.

Likewise, unless the ATAHE is specifically designed for the application, clothes dryers should not be connected directly to the exhaust system, since the lint contained in this type of exhaust may also collect on the heat exchanger surfaces. Electric clothes dryers can be vented into the laundry room through a lint filter. A separate intake can then be installed from the laundry room to the heat exchanger. Gas dryers should never be vented indoors.

Readily accessible filters should be installed in the exhaust air and fresh air ducts leading to the heat exchanger. Instructions for inspection, cleaning and/or replacement of the filters should be supplied by the manufacturer of the ATAHE.

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3.4 Exhaust Air Outlet

It is generally accepted that spacing of at least 1.5 metre is necessary to ensure against short circuiting of flows from the exhaust air outlet and fresh air inlet. Both outlet and in
designed so that wind forces affect t.
This is generally achieved by passing the ex...
and fresh air ducts through the same wall, away from corners of the house. They should also be away from driveways, above snow levels and accessible for occasional inspection and cleaning.

3.5 Duct Sizing

The minimum duct diameter should be equal to the flange on the ATAHE. A 6 or 7 inch duct is appropriate for most air flows encountered in typical homes.

The pressure drop through an air distribution system increases with the number of elbows and the duct length. As the fan capacity for most ATAHE's drops off dramatically with increased pressure drop through the ventilation system, it is extremely important to minimize elbows and duct lengths.

It is recommended that designers and installers use special care when sizing the air distribution system and that the ATAHE's, once installed, be checked to ensure that they are balanced and that acceptable air flow rates are provided.

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3.6 Noise and Vibration

Noise Control

Acoustical silencers should be installed in the supply and exhaust ducts between the heat exchanger and the interior of the house. Silencers are usually sections of duct about 1 metre long, with a sound absorbing material lining the duct.

Vibration Control

Noise generated from the operation of an ATAHE can be aggravating to the homeowner. These problems can be reduced, however, with proper ATAHE installation methods.

1) Where fans are integral components of the ATAHE, the ATAHE should be mounted with vibration isolators so that vibrations from the fans are not transmitted through the house.

Small pieces of fabric duct should be used to isolate the heat exchanger and fans from the distribution ductwork. See Figure 3.4 for a schematic of a typical noise and vibration control configuration.

2) Where fans are not integral components of the ATAHE but rather are located in the ductwork, the fans should be mounted with vibration isolators to prevent noise transmission through the house.

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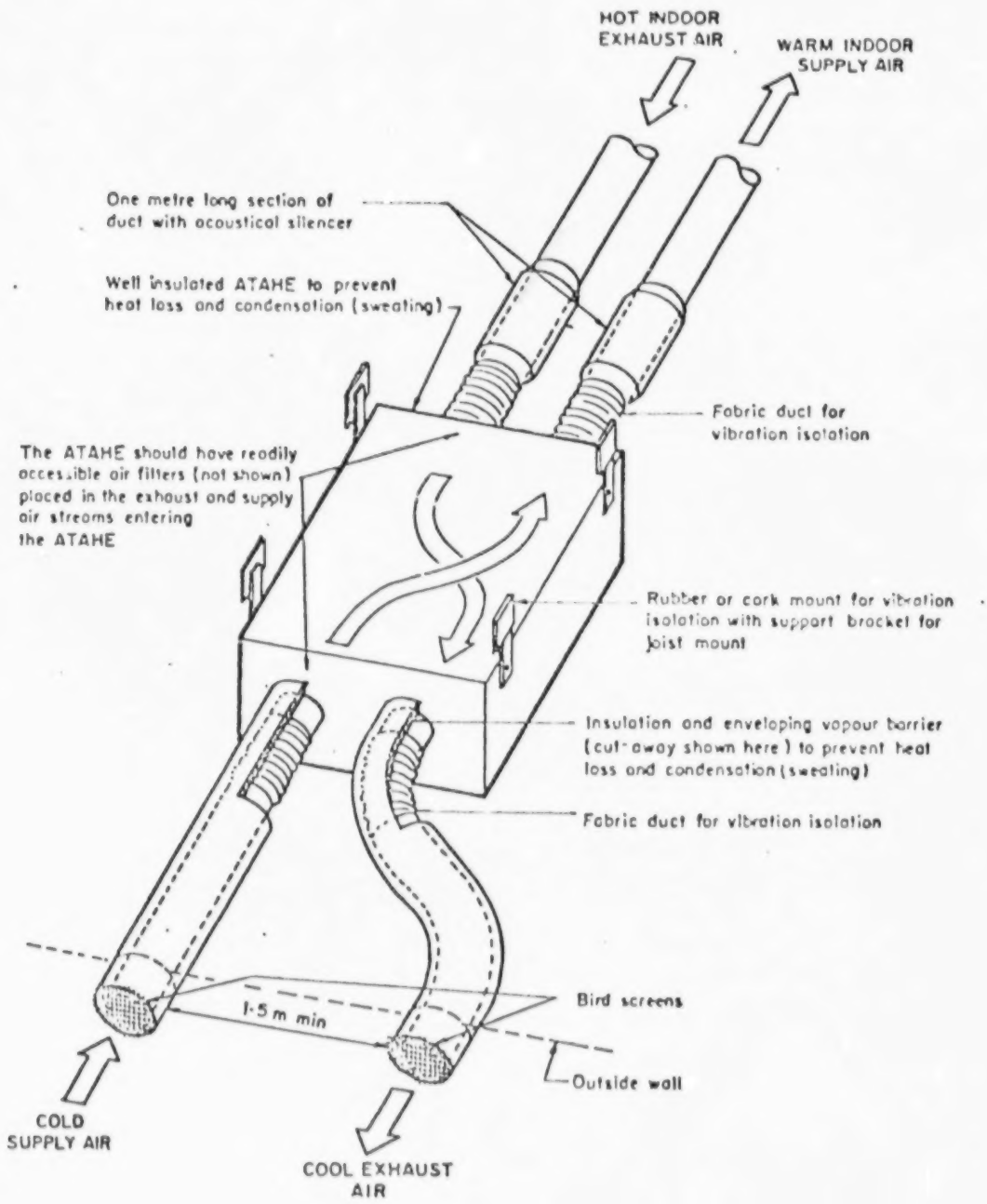
HOT INDOOR EXHAUST AIR
WARM INDOOR SUPPLY AIR
One metre long section of duct with acoustical silencer
Well insulated ATAHE to prevent heat loss and condensation (sweating)
Fabric duct for vibration isolation
The ATAHE should have readily accessible air filters (not shown) placed in the exhaust and supply air streams entering the ATAHE
Rubber or cork mount for vibration isolation with support bracket for joist mount
Insulation and enveloping vapour barrier (cut-away shown here) to prevent heat loss and condensation (sweating)
Fabric duct for vibration isolation
1·5 m min
Bird screens
Outside wall
COLD SUPPLY AIR
COOL EXHAUST AIR

FIGURE 3.4 - Noise and Vibration Isolation for an ATAHE with Integral Fans

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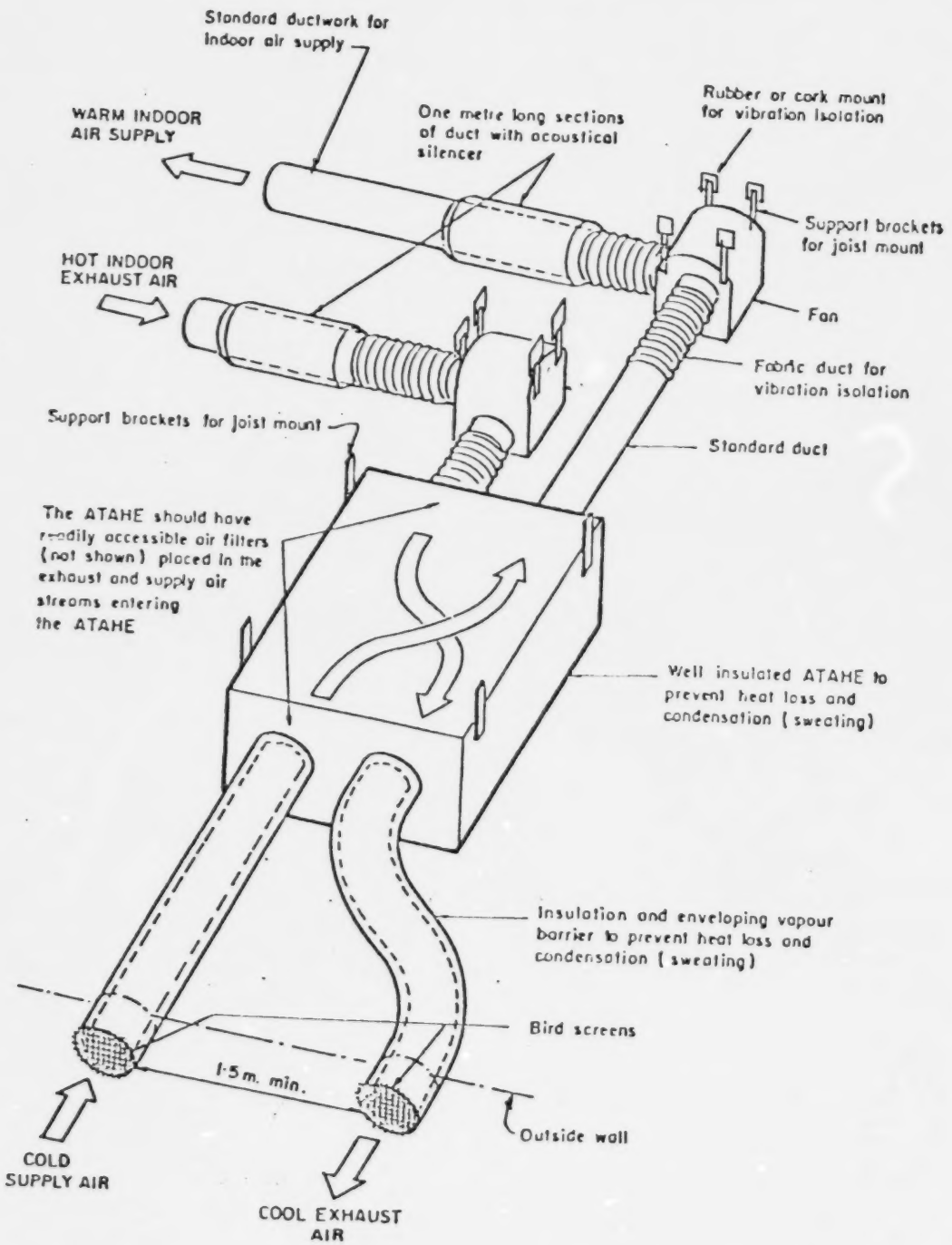
Standard ductwork for indoor air supply
WARM INDOOR AIR SUPPLY
One metre long sections of duct with acoustical silencer
Rubber or cork mount for vibration isolation
Support brackets for joist mount
HOT INDOOR EXHAUST AIR
Fan
Fabric duct for vibration isolation
Support brackets for joist mount
Standard duct
The ATAHE should have readily accessible air filters (not shown) placed in the exhaust and supply air streams entering the ATAHE
Well insulated ATAHE to prevent heat loss and condensation (sweating)
Insulation and enveloping vapour barrier to prevent heat loss and condensation (sweating)
Bird screens
1·5 m. min.
Outside wall
COLD SUPPLY AIR
COOL EXHAUST AIR

FIGURE 3.5 - Noise and Vibration Isolation with Fans Located in the Ductwork

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Small pieces of fabric duct located on either side of the fan should be used to isolate the fan from the distribution ductwork. See Figure 3.5 for a schematic of a typical noise and vibration control configuration.

When the ATAHE is located below a quiet room such as a bedroom, it may be preferrable to mount the unit on the concrete basement wall, or on a stand sitting on the basement floor rather than suspended from the floor joist.

3.7 Other Installation Notes

Application of Insulation and Vapour Barrier on Cold Ducts

During winter operation, fresh air entering the ATAHE and exhaust air leaving the ATAHE may be cold. Where these air ducts pass through the inside of the house, they should be insulated and sealed with a vapour barrier to minimize heat losses and to prevent condensation on the outside of the duct.

Ducts handling the cold fresh air and exhaust air should be kept as short as possible to reduce insulation requirements.

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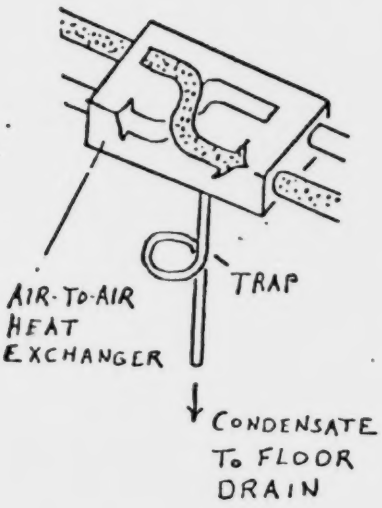
Condensate Drain



In cold weather, condensation will form on the heat exchanger surfaces inside the unit. A drain is provided on ATAHE's for removal of this condensate. This drain should be piped to a floor drain in much the same way as condensate from an air conditioning cooling coil. A trap should be incorporated in this drain.

While still in the design stage of the home, a floor drain should be placed near the anticipated location of the ATAHE.

Fire Hazards

Some ATAHE's contain significant amounts of combustible materials, such as plastics. These exchangers should be installed away from potential sources of fire, such as electrical panels, furnace flue pipes, storage cabinets, etc.

Power Supply

The electrical power requirements for most ATAHE's are generally low. Typically, there are two fan motors on the units, which require about 250 watts combined.

Some units are provided with heaters for defrosting or frost prevention. When used for frost prevention, they are often referred to as 'pre-heaters'. Defrost heaters typically have a 1 to 2 kilowatt power requirement.

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4.1 Controls

4.1.1 Two-Speed ATAHE Operation

As was previously mentioned, an ATAHE (including duct losses) should be sized to deliver 0.5 air changes per hour, the maximum ventilation rate normally needed to maintain contaminants and moisture at acceptable levels. These maximum levels are needed intermittently, generally corresponding to times when the laundry room, kitchen or bathrooms are in use. During most of the day lower ventilation rates are sufficient. Therefore most ATAHE's are designed to operate at two air flow rates, low speed for normal operation and high speed for maximum ventilation.

High speed normally corresponds to the design ventilation rate of 0.5 air changes per hour. The second, lower speed is adjustable by the installer (where fan motors have variable speed controls). The lower ventilation rate is normally set at somewhere between 0.3 and 0.5 air changes per hour. (A minimum ventilation rate of 0.3 air changes per hour may be appropriate for formaldehyde control. Out-gassing of formaldehyde is common in homes where partical board is used extensively.) This low speed setting can be adjusted to suit the particular air quality needs of the householder. For example residents who smoke may need higher ventilation rates than non-smoking residents.

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High-Speed/Low-Speed Control

ATAHE's should be run continuously. Low speed is used for normal ventilation of the home during the greater part of the day. Controls operated by a dehumidistat(s) or manual switches in the kitchen, bathrooms or laundry room can be used to run the fans at maximum speed when required. In addition, an automatic timer can activate high speed fan operation.

4.1.2 Fail-Safe Operation Sensor

Some government sponsored programs (e.g. UFFI Remedial Program) require a sensor to warn the householder that the ATAHE is not working properly. Automatic warning of improper operation can be triggered in a variety of manners, such as through detection of a stopped fan or of an abnormal pressure drop. Some are even designed to detect flow imbalances.

4.1.3 Defrost Controls

The only other control usually needed is for automatic defrosting. Under some conditions, frost can build up in sufficient quantity to raise the air flow resistance through the heat exchanger and reduce the exhaust air flow. If this reduction becomes significant, it is necessary to defrost the heat exchanger.

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Defrost Methods

Presently, various methods are used for defrosting heat exchangers. One common method is to shut off the fresh air fan while the exhaust fan continues to operate. This allows the warm air from the house to defrost the exchanger. For small heat exchangers this may be acceptable. However, for the more commonly used larger units and units in the far north where defrost requirements may be frequent, this method is probably not appropriate. Shutting down the supply air may adversely affect air quality in the home.

This defrost method will also tend to cause negative pressure in the house, resulting in potential safety problems if naturally aspirated combustion appliances are used in the home. For example, if there is a conventional gas or oil furnace, or a wood stove or fireplace, the flow in the chimney may be reversed, and combustion products brought into the house. To prevent back draft problems with combustion appliances, it is recommended that separate combustion air supplies be provided for each appliance.

An alternative method for defrosting is to use a heating coil installed at the entrance of the cold fresh air to the heat exchanger. The heating coil can be controlled in two ways. It can be turned on when the fresh air temperature falls below a certain temperature, to avoid frosting. It can also be turned on when a sensor indicates that the heat exchanger is frosting up. This method avoids placing the house under a negative pressure.

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4.2 Maintenance Requirements

The maintenance requirements for an ATAHE should be similar to those for an oil or gas furnace. Fan motors may need lubrication, or replacement if they fail. Air filters will need cleaning or replacement on a regular basis. The heat exchanger core will also probably need cleaning periodically. Some heat exchangers have a core which can be removed for cleaning. However, in some cases, the whole heat exchanger must be disconnected and removed for cleaning. The bird screen on the outdoor air intake duct must be checked periodically for blockage.

4.3 Homeowner's Manual

The builder should provide the homeowner with the ATAHE manufacturer's operation and maintenance manual. In this way the homeowner can become familiar with this new residential technology and operate and maintain the unit appropriately.

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When selecting an ATAHE, the builder should first narrow his choice by determining which ATAHE's are available with suitable rated capacities.

Characteristics of some heat exchangers available in Canada are given in Table 1.

The primary concern of the builder then becomes cost. The builder, however, should also consider the purpose of the ATAHE - to save energy, and hence money, for the homeowner. In theory therefore, the builder should attempt to balance costs versus savings:

COSTS	vs	SAVINGS
- Initial capital cost		- Projected energy savings

The cost of installation should be compared with that of a ventilation system able to achieve the same ventilation without heat recovery.

- Projected operational cost
- Projected maintenance cost

The ATAHE can then be selected on the basis of reasonable payback and return on investment. Additionally, there are intangible factors which should be considered, associated with convenience, safety and dependability.

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DRAFT

In practice, however, it is difficult if not impossible for a builder to purchase an ATAHE based on an analysis of costs versus savings because savings are difficult to estimate.

For example, defrost requirements are not easily predicted. As well, as previously mentioned, the effectiveness ratings which are needed to estimate savings cannot be directly compared because of the lack of standardized test methods.

For the present, a builder may wish to select an ATAHE based primarily on factors and features such as the following:

- Air flow capacity
- Thermal effectiveness
- Defrost operation
- Ease and simplicity of ATAHE maintenance and cleaning by the householder
- Noise level
- Control options

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An ATAHE should be chosen considering a variety of factors, including air flow requirements, the effectiveness of the unit and the cost (capital, installation and maintenance).

When designing or retrofitting a well-sealed home, the following are some points to consider regarding installation and operation of an ATAHE.

Design and Installation

- The designer should design the HVAC system to minimize space required for HVAC equipment and to incorporate safety.

- The outdoor intake and exhaust should be at least 1.5 metre apart, located to be free from snow and leaves.

- The outdoor intake and exhaust should be designed so that wind forces effect each equally.

- Outdoor intake and exhaust ducts, because they carry cold air streams, should be insulated and have an air barrier to prevent condensation. These ducts should be as short as possible to reduce heat loss and insulation requirements.

- The intake should contain a coarse screen.

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- Stale air entering the heat exchanger should come from areas of high contaminant and moisture levels, such as kitchen, bathrooms and utility room.

- Fresh air exiting the heat exchanger should be vented directly to individual rooms if baseboard heating is used, and to central location near the return air duct if a central forced air heating system with intermittent fan operation is used. For central forced air heating systems using constant air circulation, the ATAHE can be connected into the return air ductwork, unless prohibited by local codes.

- Air filters should be located in the exhaust air and fresh air ducts leading to the heat exchanger.

- A drain should be provided near the ATAHE for condensate. The condensate line should contain a trap.

- The ATAHE should be installed away from sources of heat and fire hazards (e.g. furnaces, electrical panels, storage cabinets).

- Vibration isolators and acoustical silencers should be used.

- The fresh air and exhaust air flows should be tested after the ATAHE is installed to ensure the flows are balanced and that they meet the design rate.

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DRAFT

WILLIAM A. SHURCLIFF
19 APPLETON STREET
CAMBRIDGE, MASSACHUSETTS
02138

2 10/13/83

Dear Dara Bowser of AirChanger Co. Btd.:

Thanks for Sept. 26 letter.

I must say I agree with your main conclusions:

To get eletrical-power-consumption of heat-recovery ventilators very low would be very difficult,

Keeping defmost power very low may be equally important-- and is usually overlooked by most people (including me, alas).

***

Since Prof. Besant issued his report, a few months ago, on the horrific cross contamination of Fan-X-Changer, I have heard nothing from him or from P.M.Wright Co. or from Brian Tollerof "Renewable Energy News". I sent news and inquiries to all of them, but no answers! I remain aghast at the big cross-contamination figure and at what I presume to be very low efficiency. Should not P.M. Wright Co. withdraw the product entirdy?

Best wishes,

Bill

William A. Shurcliff

PS: My impression is that I never sent to you a copy of my blast concerning Fan-X-Changer. So, I'm sending herewith a sheaf ofpapers on that subject.- my 7/2$/83 memo. with accompanying xeroxes of P.M. Wright literature and accompanying 5/16/83 ltr. to Toller, and 6/25/83 ltr. to Lamarche of P. M. Wright Co.

JUN 1 1984
DEPT.

RECEIVED
OCT 18 1983
ALLEN-DRERUP-WHITE
LTD.

CAMBRIDGE, MASSACHUSETTS
02138

7/29/83

To: Air-to-Air Heat-Exchanger Experts

For some time I have been concerned about some of the claims made by P. M. Wright, Ltd., of 1300 Jules-Poitras, St.-Laurent, Montreal, PQ, CANADA H4N 1X8, for its "Fan-X-Changer" air-to-air heat-exchanger designed for use in houses -- the Model WR25. I have in mind especially these claims:

"Efficiency up to 80%" and "... renders obsolete most other systems."

A letter expressing my concern was published in the (Canadian) Renewable Energy News of May 1983, and that same issue carried a reply by P. J. Lanarche of P. M. Wright Ltd.

Wright's reply seemed either unclear or incorrect or both. Accordingly I wrote to him, on 6/25/83, a long letter criticizing that reply. I am enclosing a copy of this letter -- to which, in over a month, I have received no reply.

I would be glad to learn of any thoughts you may have as to the claims in question, or as to what steps might be taken. The device clearly has some good features, such as compactness, simplicity, low cost; but it would be unfortunate if unsound claims were included with sound ones.

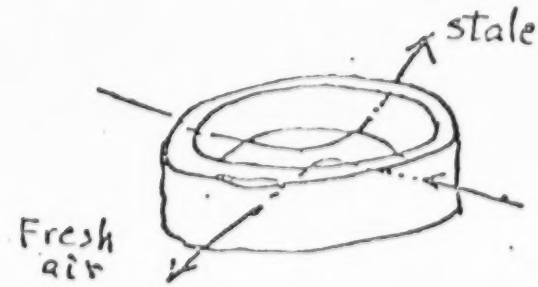
The same (?) device, under the name Temp-Recycler, is marketed by Forex Corp. of 105 Liberty, Walled Lake, MI 48088; I received from Robert P. Jones of that company a helpful letter. All of his views seemed to me reasonable.

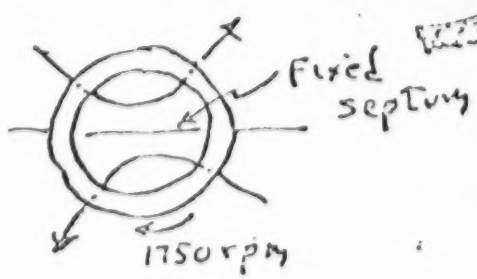
Sincerely,

William A. Shurcliff PhD.

Author of books on solar heating, air-to-air heat-exchangers, etc.

PS: It has just now occurred to me that an additional pair of claims deserves scrutiny: "Capacity: 210 cfm each side...", "Motor: 110 v, 60 Hz, 1.2 amps." Is it reasonable that a device that employs such a crude impellor (plastic foam ring) can produce two such large (210 cfm) airflows while consuming only 110 v times 1.2 amp., or about 130 watts? Each airstream must pass through the foam ring twice; must pass through an area of only about 20 sq. in. (my guess), and must have there a linear speed of about 20 ft/sec. (my estimate). Each air molecule has only about 1/100 sec. to travel inward through the ring and reverse its direction and travel outward through the ring. I expect that turbulence is great. I would be surprised to find that a mere 130 watts could produce two 210 cfm flows, especially when and if the device is associatdd with inlet grill, filter, inlet duct, outlet duct, outlet grill, and a supplementary electrical heater.





MAIL THIS POSTAGE PAID REPLY CARD TODAY

BUSINESS REPLY MAIL
No postage stamp necessary if mailed in Canada

Postage will be paid by

P.M. Wright Ltd.
1300 Jules-Poitras
Montreal, Que.
H4N 9Z9

POSTES · CANADA · POSTAGE 1540

FAN-X-CHANGER

DESCRIPTION

1 single fan combining 3 functions (Exhaust Fan, Supply Fan, Energy Recovery).
A fan consisting of a capillary wheel transfers energy from the warm exhaust air to the incoming fresh air. The recovery rate is up to 80% total.

No need to pre-heat the incoming fresh air.

APPLICATIONS

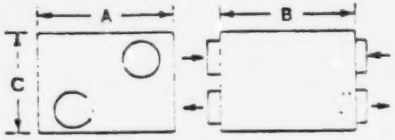
- Fresh-air make-up for general ventilation.
- De-humidifies the air within the house.
- Fresh-air make-up improves furnace and fireplace combustion.
- Swimming pool and whirlpool ventilation

FEATURES

Compact	— ⅓ size of conventional units
Easily Cleaned	— Without taking apart or messy washing
No Freeze-up	— No need for complicated defrost systems and resulting nuisance shutdowns
High Capacity	— Variable speed 100 to 210 C.F.M.
Extremely Quiet	— Vibration free (50 dB)
Recovers Year Round	— Helps cool house in summer

Attractive cost & simplified installation

SPECIFICATIONS



Dimensions:
A- 40 cm (16")
B- 33 cm (13")
C- 30 cm (12")

Duct connections: Round - 6" dia.
Weight: 10kg (22 lbs.)
Capacity: 210 C.F.M. each side down to 90 C.F.M.
Ext. Stat. Pr.: 22 mm (0.9" water)
Motor: 110 V, 60 Hz, 1.2 amp.
Recovery: Up to 80% total
Noise Level: Very quiet 50 dB

Note: For larger capacities consult factories or agent.

P.M. Wright Ltd.

Montreal: 1300 Jules-Poitras, Montreal, Que. H4N 1X8
Tel.: (514) 337-3331 • Telex: 05-826893

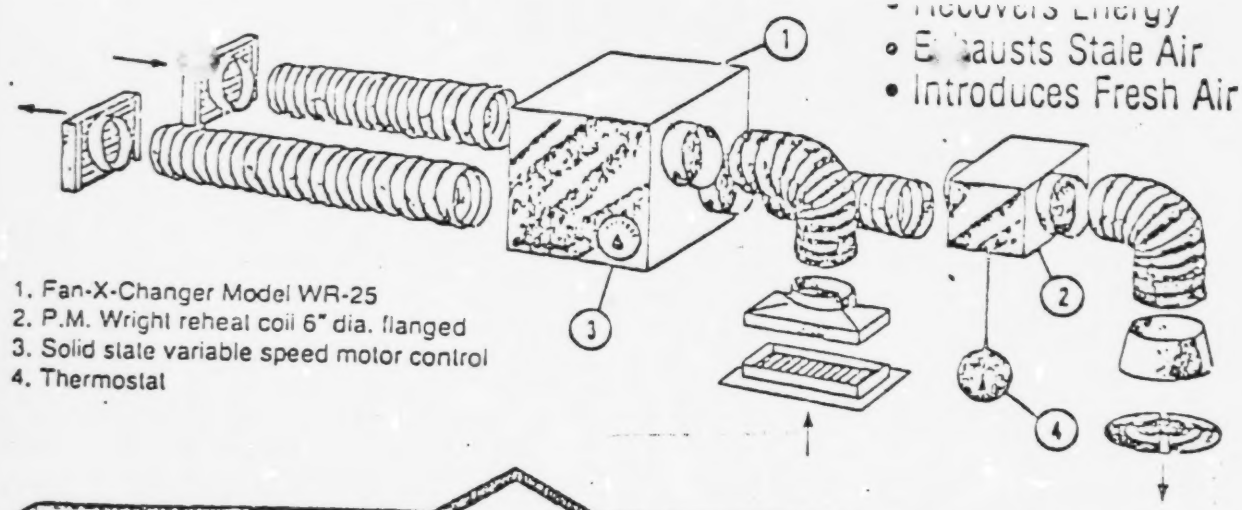
Toronto: 1111 Finch Ave. West
Downsview, Ontario M3J 2E5
Tel.: (416) 665-8733 • Telex: 06-219643

Quebec: 230 - 78th St. East Charlesbourg, Quebec
G1H 1C9 Tel. (418) 626-7034

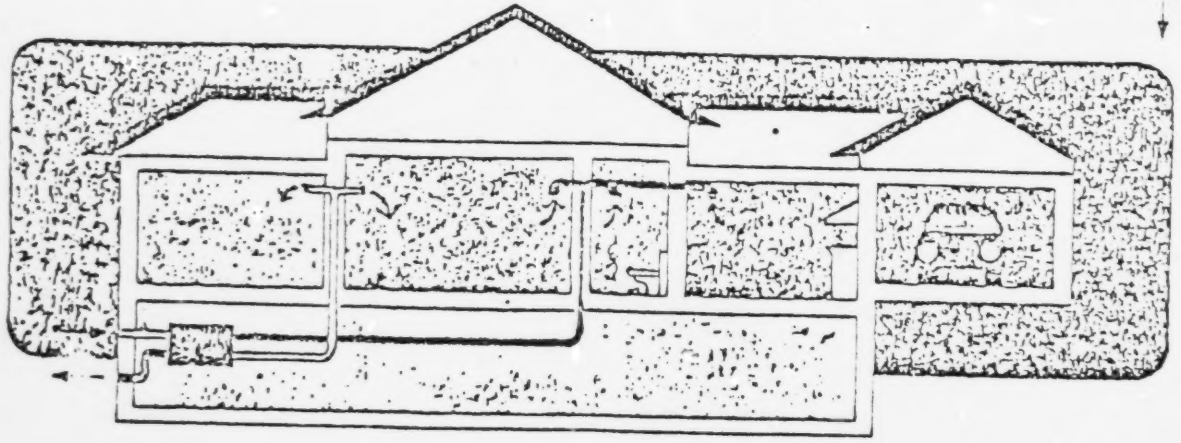
FAN-X-CHANGER

An original concept from Europe providing Energy Recovery and Ventila

- Recovers Energy
- Exhausts Stale Air
- Introduces Fresh Air



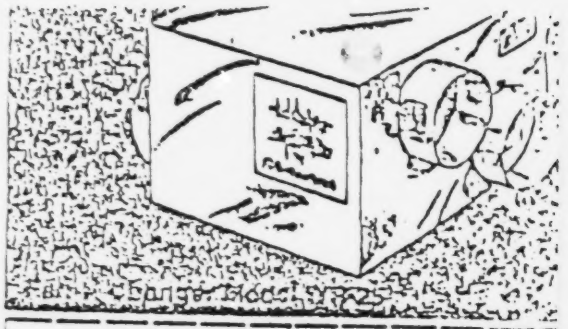
1. Fan-X-Changer Model WR-25
2. P.M. Wright reheat coil 6" dia. flanged
3. Solid state variable speed motor control
4. Thermostat



In today's better insulated homes improper air ventilation can pose serious problems. Humid stale air, high humidity or even worse the accumulation of toxic gases like formaldehyde, nitrous oxides, even radon can easily build to dangerous levels. To combat these problems, P.M. Wright introduces the Fan-X-Changer, an air-to-air heat exchanger which supplies warm fresh air throughout your home while at the same time exhausting cool stale air, thereby recovering energy and saving you money. Fresh air and a healthy environment is important to the good health of your family, pets and plants, while contributing to the preservation of your furniture and home.

- FAN-X-CHANGER introduces a whole new concept which outperforms other systems.
- Efficiency up to 80%.
- Equivalent efficiency compared to conventional heat exchangers which recover sensible heat only.

YOUR DEALER



P.M. Wright Ltd.
1300 Jules-Poitras
Montreal, Quebec
H4N 1X8

I'm interested in the Fan-X-Changer's energy recovery & ventilation features.

☐ *Please send me more information.* ☐ *Please have a representative call me for an appointment without obligation.*

Name
Address
City
Prov.
Tel.

19 APPLETON STREET
CAMBRIDGE, MASSACHUSETTS
02138

Mr. Brian Toller, Publisher,
Renewable Energy News,
CREN Publishing Ltd.
58 Arthur St., Second Floor,
Ottawa, CANADA K1R 7B9

5/16/83

Dear Brian:

I am writing concerning the large advertisement appearing on p. 10 of the May 1983 REN: the advertisement by P. M. Wright Ltd. for its "Fan-X-Changer" air-to-air heat exchanger. My fear is that a certain central statement in the advertisement will mislead your readers and unfairly penalize manufacturers of exchangers of standard (countercurrent) type.

After corresponding at length with P.M. Wright Ltd., I believe I understand the principle of operation of their exchanger. As I understand it, the exchanger is, in effect, of concurrent type: in effect, the old air and new air sweep past, or through, the energy-absorbing device in the same direction, rather than in opposite directions. In a standard concurrent device, the thecretical upper limit on efficiency of sensible heat recovery (assuming equal airflows in the two airstreams) is 50%, and in practice one achieves an efficiency of only about 40%. My impression, from information sent to me by P. M. Wright Ltd., is that, with respect to recovery of sensible heat, their Fan-X-Changer has an actual efficiency near 45%.

Regarding efficiency of recovery of latent heat: If the outgoing air has higher absolute humidity than the incoming air has, some transfer of water molecules will occur; that is, some latent heat will be recovered. But, typically, the recovered energy has the form of latent heat -- not sensible heat. Thus it does not contribute to warming the incoming air: its contribution has the form of added humidity only. Added humidity may or may not be wanted. If the room air tends to be too humid, increasing the humidity is a disservice.

Now consider air-to-air heat-exchangers of conventional type, i.e., countercurrent type. About twenty types are commercially available. Nearly all of these have sensible-heat-recovery efficiencies of 60 to 80% typically, and if the airstreams are slowed down (by reducing the power supplied to the blowers), efficiences as high as 90% or higher may be obtained. Some models recover, also, nearly all of the latent heat.

If I am right in believing that the Fan-X-Changer has only a little more than half the heat-recovery efficiency of conventional air-to-air heat-exchangers, should not one challenge the claim (made in the above-mentioned advertisement) that the Fan-X-Changer introduces a concept "...which renders obsolete most other systems"? Is not such a claim misleading to readers and unfair to the manufacturers of conventional exchangers?

Sincerely,

Bill

William A. Shurcliff

10 APPLETON STREET
CAMBRIDGE, MASSACHUSETTS
02138

6/25/83

Mr. P. J. Lamarche, V.P. Marketing,
P. M. Wright Ltd.,
1300 Jules-Poitras,
St.-Laurent, Montreal, PQ, CANADA H4N 1X8

Dear Mr. Lamarche:

Thank you for your June 14, 1983, letter and for the 11/3/82 report you sent with it -- a report that presents various efficiency calculations purporting to show that your company's Fan-X-Changer air-to-air heat-exchanger is superior to other companies' exchangers. Your letter comments on my letter of 5/16/83 to Brian Toller, Editor, "Renewable Energy News"; my letter was critical of a claim made in your company's advertisement in the May '83 issue of that periodical.*

I agree with your statement that the Fan-X-Changer is especially small, simple, and inexpensive. But I do not consider these characteristics to be of central importance.

What is of central importance in an air-to-air heat-exchanger is the efficiency, and in particular the efficiency with respect to transfer of sensible heat.

The 11/3/82 report you enclosed deals at length with heat transfer efficiency, but does so in a manner that seems to me unsatisfactory. Several basic assumptions seem unsatisfactory and the conclusions likewise.

The calculations presented in the first half of p. 1 of that report seem correct, except that the resulting values of heat recovery are about 3% too small, apparently because the figure used for the density of air was the value for air at about 70 to 90°F, rather than the (slightly greater)value -- 0.080 lb/ft^3 -- appropriate for air at about 40°F.

But I do take issue with the main assumptions made.

***

One unsatisfactory assumption is that other manufacturers' exchangers do not recover moisture (and thus do not recover the enthalpy associated with the moisture). By comparing your exchanger (which does recover moisture) with exchangers that do not recover moisture, the authors of the 11/3/82 report come up with comparative figures that make your exchanger appear superior. In fact, some other exchangers recover moisture -- and its enthalpy. For example, the "Economini 500", manufactured in Woburn, Mass., by Berner International Corp.; that exchanger provides three flow-rates, up to 295 cfm, and costs about $1100. My guess is that it has higher freedom from cross-contamination than the Fan-X-Changer and also has higher efficiencies of every kind. Do you have any figures showing how the Fan-X-Changer and Economini compare?

---

*The claim: "Fan-X-Changer renders obsolete most other systems".

***

Another unsatisfactory assumption is that moisture-non-recovering exchangers (i.e., the class that includes the great majority of exchangers) are operated in such a way that the outgoing air never becomes colder than 32°F. The assumption is expressed in these words:

> "No latent heat transfer allowed because heat transfer characteristics of sensible device are unknown in condensation mode. If unit is run in condensation mode, dust build up on the unit could increase dramatically."

My understanding is that, in zero-degree weather, such exchangers are routinely operated in such manner that outgoing air cools down far below 32°F. As it does so, much moisture is condensed. A suitable drain is provided, and many gallons of water may drain out each day. (Occasional defrosting cycles get rid of the ice.) When the moisture condenses -- forming water or ice --an enormous amount of latent heat is converted to sensible heat. Normally the great majority of this finds its way (via the thin membranes of metal or plastic) into the incoming airstream. Thus if the indoor air is at 72°F and the outdoor air is at 0°F (as in the example cited in the 11/3/82 report), the temperature of the incoming air, as it emerges from the exchanger and enters the rooms, may be as high as, say, 60°F. In other words, the efficiency with respect to delivery of sensible heat may be about 60/72 = 83%. If may be even higher if the flow-rate is reduced. The theoretical upper limit is, of course, 100% -- if the exchanger is of countercurrent flow type.*

But the authors of the 11/3/82 report, proceeding from their peculiar assumption, conclude (per p. 1 of the report) that the pertinent upper limit on efficiency of these competing exchangers, in the given case, is only 55.5%.

I regard the assumption, and the conclusion, as unsatisfactory.

I wonder what the authors of that report mean when they say that "heat transfer characteristics of sensible device are unknown in condensation mode." Unknown to whom?

Also, what is one to make of the sentence: "If unit is run in condensation mode dust build up on the unit could increase dramatically"? I believe most exchangers contain filters to intercept dust. Also, I would expect that the steady production and draining of water would carry away most of any dust that is deposited.

***

Another assumption, tacit in pages 2 and 3 of the report, is that recovery of moisture (and the latent heat associated therewith) is a valued aspect of exchanger performance. But are not most exchangers operated mainly in winter and mainly in tight buildings? And is not the air in such buildings, at such time, too humid, ordinarily? Of course, under some circumstances the indoor air is too dry and the recovery of moisture is helpful; but, ordinarily, is not the transfer of moisture to the incoming air a disservice? Pages 2 and 3 of the report seem to imply that the latent heat associated with moisture transfer is fully as valuable as sensible heat. Is not such implication, or assumption, incorrect?

---

* The general procedure I am using here is explained in detail on p. 62 of my book "Air-to-Air Heat-Exchangers for Houses", Brick House Publishing Co., 34 Essex St., Andover, MA 01810. 1982. $13.

My understanding is that latent heat of humidity can be converted to sensible heat by condensation process only, and, ordinarily, no condensation occurs in Fan-X-Changer, and accordingly that device ordinarily converts no latent heat into sensible heat. Am I right on this point?

***

Another assumption (see p. 2 of the 11/3/82 report) is that the Fan-X-Changer has a sensible heat transfer efficiency of 50% and a latent heat transfer efficiency of 50%. Is it not true that these figures are merely the ideal upper limits of any concurrent-flow exchanger? Is it not true that the actual efficiencies are lower? Are they, I wonder, as low as 40%? In any event, did not the authors of the 11/3/82 report err in assuming 50% sensible-heat efficiency and 50% latent-heat efficiency?

***

I am mystified by the heading "ΔT Equivalent", and associated equation, at the bottom of p. 2 of the report. What does "ΔT Equivalent" mean? Are the authors under the impression that the combination of added sensible heat and added latent heat in the form of moisture implies an air temperature higher than that provided by the added sensible heat alone? That is, are they under the impression that latent heat in the form of moisture can raise the temperature of the air? They seem to be under this impression -- because they proceed to compute the temperature 48.9 °F, which is higher than the temperature that the sensible heat alone would produce. And they proceed further: they compute an "Equivalent efficiency" equal to 48.9/72 = 67.8%. This is higher than the ideal sensible heat efficiency (50%)! Higher than the ideal latent heat efficiency (50%)! I can only guess that the authors are unaware that recovered latent heat that is in the form of moisture, or humidity, cannot contribute to a rise in temperature of the air in question. (Am I right? Or have I somehow misread the report?)

The small, folded, many-color brochure you sent includes the sentence "The recovery rate is up to 80% total". Was this figure arrived at by the same line of reasoning discussed above? Is it, accordingly, invalid?

Note that if the above-discussed line of reasoning were applied to an exchanger that had 75% sensible-heat-recovery efficiency and 75% latent-heat-recovery efficiency, one might conclude that the "Equivalent efficiency" exceeds 100%!

***

Has any well-known, impartial testing company evaluated the efficiency of Fan-X-Changer devices made by your company? If so, is their report available?

Sincerely,

William A. Shurcliff

William A. Shurcliff PhD

Honorary Research Associate,
Physics Dept.,
Harvard Univ.

Copy sent to: Brian Toller, Editor,
Renewable Energy News

10 APPLETON STREET
CAMBRIDGE, MASSACHUSETTS
02138

7/7/83

Letters-to-the-Editor Editor,
"Renewable Energy News"
PO Box 4869, Stn. E,
Ottawa, Ont., Canada K1S 5J1

NOT FOR PUBLICATION

Dear Sir:

I have just read, on p. 6 of your July issue, my letter "Heat Exchanger Ad Misleading" and the reply by P. J. Lamarche of P. M. Wright Ltd.

His reply fails to counter any of my statements and it includes several remarks that seem wrong or foolish or both. The enclosed letter-copy (copy of my 6/25/83 letter to him) explains why his remarks are wrong or foolish. I am inclined to think that he does not have a good understanding of how heat exchangers operate or how their performance is to be appraised.

I'm hoping he will reply to me soon -- I want to give him a chance to find out where, if at all, I have misread his letter or misread his report.

I expect to mail off a formal letter (for publication) to you in a couple of weeks, i.e., a letter pinpointing the errors in Lamarche's letter appearing in your July REN. *

Sincerely,

William A. Shurcliff

William A. Shurcliff

*That letter by Lamarche includes two misstatements:

"...conventional exchangers only recover sensible heat..".
Not true. Several conventional exchangers (for example, two models sold by Berner International Corp.) routinely recover latent heat in addition to sensible heat; and they do so over a very wide range of conditions. Also, nearly all other exchangers, when operated at times when the outdoor temperature is low and condensation occurs (moisture in the outgoing air is converted to liquid water or to frost), convert some latent heat into sensible heat.

"(conventional exchangers) work at a very limited delta-T (when used in cold climates)".
Not true. Most of them operate over a wide delta-T. Some have automatic defrost and can perform well even over a very wide delta-T.

CROSS CONTAMINATION IN A FAN-X-CHANGER HEAT EXCHANGER

RECEIVED
NOV 18 1983

JULY 1983

ROBERT W. BESANT

AND

JOHN KARCHEWSKI

DEPARTMENT OF MECHANICAL ENGINEERING

UNIVERSITY OF SASKATCHEWAN

DEPARTMENT OF [illegible]
AND CORPORATE AFFAIRS
REGIONAL MANAGER
JUN 1 1984
UFFI DEPT.

RECEIVED
OCT 24 1983
ALLEN-DRERUP-WHITE
LTD.

INTRODUCTION

As the demand for energy efficient buildings increases, a need for cheaper and more efficient air-to-air heat exchangers arises. The Fan-X-Changer heat exchanger was developed with these criteria in mind. It has several interesting characteristics.

1. A single motor and fan
2. High heat transfer rates claimed by the manufacturer
3. Small size and compactness
4. No frosting problems claimed by the manufacturer
5. Low cost

This report evaluates an apparent problem—cross contamination of the exhaust and fresh air streams. The test was accomplished by simulating various loading conditions and following the flow in each case. The path of the flow was monitored using a tracer gas, nitrous oxide (N_2O).

TEST APPARATUS

The test apparatus consisted of a Fan-X-Changer heat exchanger with the necessary ducts. Figure 1 shows the configuration used. Also, to determine the quantity of nitrous oxide in each of the samples, a Beckman 865 Non-Dispersive Infrared Analyzer was used.

The pitot traverse was performed using a Fluke 1720A Instrument Controller, a Fluke 8860 Multimeter, a LCVR 0-2 cm Pressure Transducer and a pitot tube.

TEST PROCEDURE

The test apparatus, as shown in Figure 1, was tested under four

different flowrates. These flowrates were altered using simulated loads.

The samples were taken in a standard order. (The order is specified in Figure 1.) The specific order that the samples were taken was not important except that, since sample #4 is a measure of the laboratory contamination level, it was taken last.

During each test run, the equipment was allowed approximately five minutes to stabilize before any samples were taken. Usually, two samples were taken at each location for an indication of the sampling error. The same order as above was maintained except the cycle was repeated twice.

Each test run took a maximumm of five minutes and after each one, the samples were tested for the nitrous oxide content.

The four flowrates were found by performing a ten-point, equal area pitot traverse. The equipment for this traverse was as previously described.

RESULTS

The cross-contamination that occurred in the Fan-X-Changer is recorded in Table 1 and Figure 2. Note that the maximum flowrate was 0.075 m^3/s when unloaded and subsequently no tests were performed with a higher flowrate. Also, no tests with smaller flowrates than 0.034 m^3/s were performed since 50% contamination had already been reached.

DISCUSSION

The Fan-X-Changer heat exchanger performed poorly in the cross-contimination tests. With no load, the heat exchanger had

cross-contamination levels of about 17%. When loads were applied, these results climbed (see Figure 2). The worst possible case of 50% cross-contamination was found at about 0.034 m^3/s (2040 ℓ/min). These tests seem to indicate that the manufacturer's claims of minimum sensible and latent heat transfer of 48% and 46%, respectively, (see attached brochure by P.M. Wright Ltd.) may be largely due to the mixing of the two streams. (Also included is a recent report taken out of Energy Management Canada on heat exchangers in general.)

The measured static pressure change across the heat exchanger averaged 0.20 kpa (20.6 mm H_2O) when the total flow rate into the heat exchanger averaged .064 m^3/s. Such a pressure change across the heat exchanger is likely large for most good installations which might more typically be half of the above value of .2 kpa. This would suggest that the typical contamination would be about 35 percent as given in Figure 2 or 35 percent of the exhaust air would be returned to the building through the fresh air duct of the heat exchanger.

SUMMARY

This report investigates the cross-contamination of air streams in a Fan-X-Changer air-to-air heat exchanger. The results show that, depending on the heat exchanger load, the cross-contamination varies from 17% to 50% when the static pressure change across the heat exchanger increased from 0 to 17.7 mm of water (0 to .174 kpa) and the flow rate decreased from .148 m^3/s to .069 m^3/s.

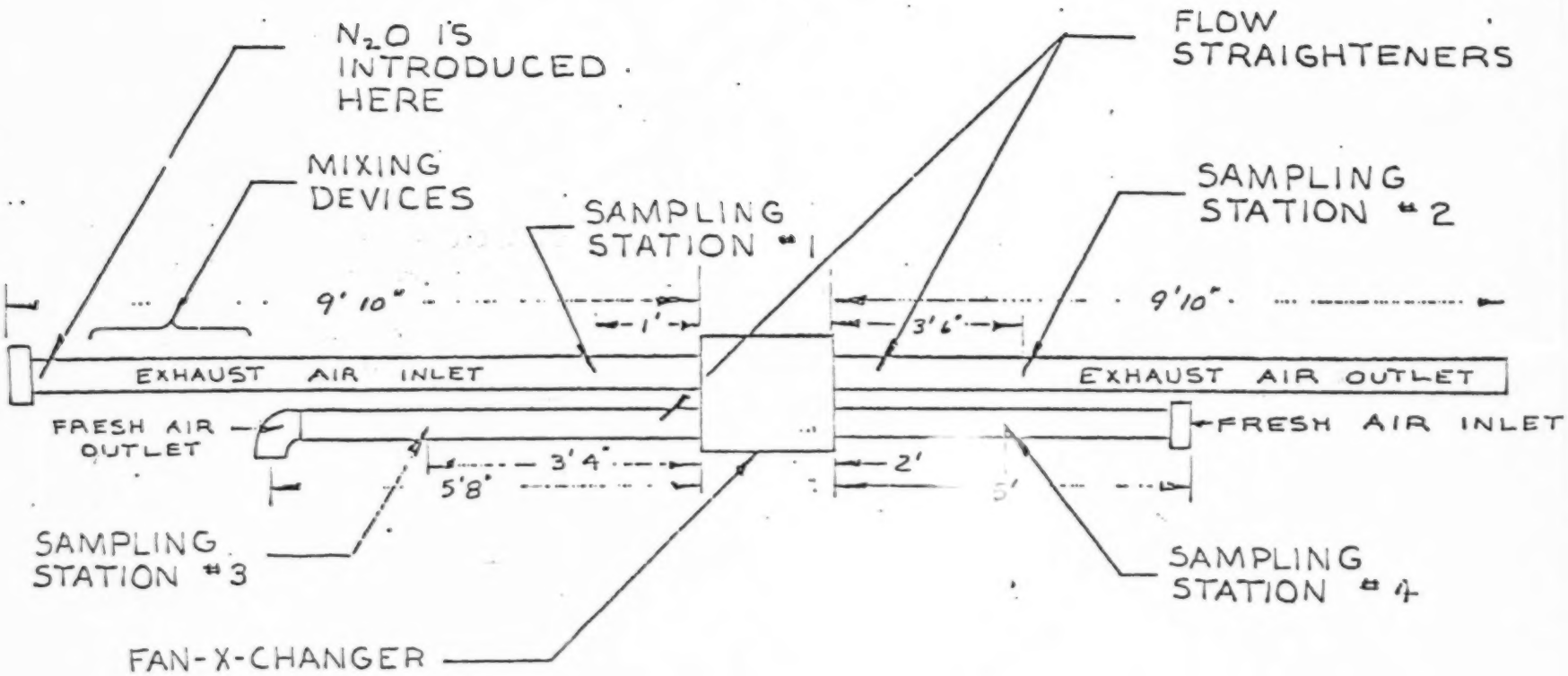
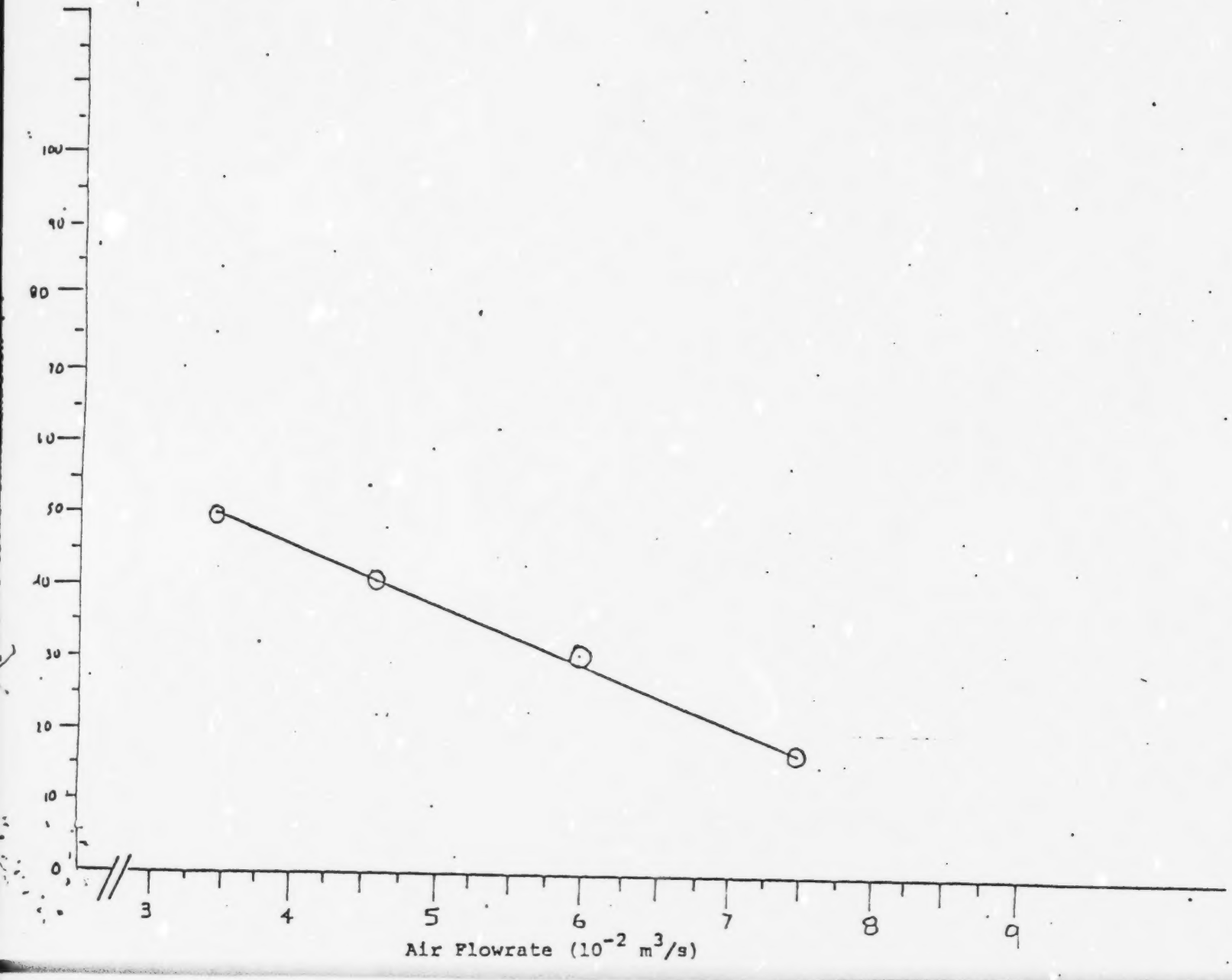


FIG. 1: TESTING APPARATUS

RUN #	N_2O (RECORDED) HOT AIR IN (PPM)	HOT AIR OUT (PPM)	COLD AIR IN (PPM)	COLD AIR OUT (PPM)	VOLUME FLOWRATE OF AIR (m^3/s) HOT AIR IN	HOT AIR OUT	COLD AIR IN	COLD AIR OUT	VOLUME FLOWRATE OF N_2O ($10^{-6} m^3/s$) HOT AIR IN	HOT AIR OUT	COLD AIR IN	COLD AIR OUT	A*
1	90.7 68.0	73.1	--	14.9	0.06723	0.07474	0.07946	0.07562	6.098 4.572	5.463	--	1.127	17.1
2	71.35 76.85	70.5	--	16.0	0.06723	0.07474	0.07946	0.07562	4.797 5.167	5.269	--	1.210	18.7
3	82.15 76.9	66.85	0.9	13.65	0.06723	0.07474	0.07946	0.07562	5.523 5.170	4.996	0.07151	1.032	17.1
4	71.55 83.3	67.5 63.6	0.9 1.2	12.5 13.25	0.06723	0.07474	0.07946	0.07562	4.810 5.600	5.045 4.753	0.07151 0.09535	0.9453 1.002	15.8 17.4
5	87.5 88.0	59.4 59.1	1.3 1.9	23.4 24.2	0.05390	0.05693	0.06349	0.06312	4.717 4.744	3.382 3.365	0.08253 0.1206	1.477 1.527	30.4 31.2
6	86.6	71.45	1.5	26.8	0.05390	0.05693	0.06349	0.06312	4.668	4.068	0.09523	1.691	29.4
7	75.65	57.35	1.95	23.6	0.05390	0.05693	0.06349	0.06312	4.078	3.265	0.1238	1.490	31.3
8	111.9 102.2	59.7 58.7	1.1 1.4	39.9 40.8	0.04867	0.04416	0.04711	0.04326	5.446 4.974	2.637 2.592	0.05182 0.06595	1.726 1.765	39.6 40.5
9	72.2 72.5	42.75 45.6	0.7 1.2	28.9 31.85	0.04867	0.04416	0.04711	0.04326	3.514 3.528	1.888 2.014	0.03298 0.05653	1.250 1.378	39.8 40.6
10	76.5 79.5	35.3 37.65	1.6 1.0	41.5 41.1	0.03097	0.03616	0.03764	0.03315	2.370 2.462	1.277 1.362	0.06023 0.03764	1.376 1.363	51.9 50.0
11	72.2 77.7	42.9 35.7	1.1 1.9	39.8 40.5	0.03097	0.03616	0.03764	0.03315	2.236 2.407	1.551 1.291	0.04141 0.03764	1.320 1.343	46.0 51.0

*A = $\frac{N_2O \text{ VOL. FLOW (COLD AIR OUT)}}{N_2O \text{ VOL. FLOW (COLD AIR OUT)} + N_2O \text{ VOL. FLOW (HOT AIR OUT)}}$

TABLE 1: CROSS CONTAMINATION DATA


100
90
80
70
60
50
40
30
20
10
0
3
4
5
6
7
8
9
Air Flowrate (10^{-2} m^3/s)